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REPORT

MRL-R-1016

**A CALIBRATED TEST FOR THE ASSESSMENT OF THE
SENSITIVITY OF EXPLOSIVES TO SHAPED CHARGE JETS**

M.C. Chick, M.G. Wolfson and L.A. Learmonth

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The steel cover thickness was calibrated in order that sensitivity values can be expressed as a function of the critical jet velocity at the detonation/failure threshold.

Some explosive sensitivity values are reported for both the covered and bare configurations. Generally, explosives in the bare state were found to be significantly more sensitive than when covered.

A method of instrumenting the test with multiple flash radiography is described and the mechanisms of jet initiation of explosives are summarised.

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A CALIBRATED TEST FOR THE ASSESSMENT OF THE SENSITIVITY OF EXPLOSIVES TO SHAPED CHARGE JETS

1. INTRODUCTION

Explosive fillings in munitions are common targets in both war and peacetime for the high velocity jets produced from shaped charges. Typical of such situations are the destruction of obsolete and dangerous munitions by Explosive Ordnance Disposal (EOD) techniques and the attack (by enemy and guerilla forces) of munitions in storage, transport and use. An example of the former is the removal of sea mines placed in friendly strategic waterways. Examples of the latter include the threat to stocks of bombs, shells and warheads in magazines, ammunition inside armoured vehicles and missiles on ships.

In the past, the majority of work investigating jet/explosive target interactions has been directed towards the engineering applications of the penetration of live or simulated munitions. Much of the information is in the classified literature but even so the results apply to particular, complicated ordnance systems and shed little light on the basic understanding of the processes involved in the jet initiation of covered and bare explosives. The exceptions have been a preliminary study by Zernow et al [1] on steel covered Composition B, work by Held [2] and Mader and Pimbley [3] on bare explosives and a study by Frey et al [4] on confined Composition B.

In the early 1970's the Materials Research Laboratories (MRL) commenced a program to study the vulnerability of explosives to shaped charge jets in order to produce comparative sensitivity data for various munition fillings and to develop an understanding of the controlling parameters and mechanisms of initiation. Important aims of the work were to improve the predictive and diagnostic methods in jet/explosive filling interactions and to assist in the design of protection techniques and vulnerability analysis.

This report describes the calibrated test developed for assessing the sensitivity of covered and bare explosives to the jet from the MRL 38 mm diameter shaped charge. Some results are presented and the current understanding of the mechanisms of initiation are summarised. Detailed discussion of the latter are given elsewhere [5-9].

2. THE JET SENSITIVITY TEST

2.1 Test Design and Assembly

The test was developed at MRL in the early 1970s to investigate the sensitivity of both bare and covered explosives to shaped charge jets. The form of the test assembly was designed to simulate the cross section through a munition case and explosive filling penetrated by a shaped charge jet. This is illustrated in Figure 1. The actual assembly for the testing of explosive in the covered configuration is shown diagrammatically in Figure 2. Measurements on bare explosives are carried out with a similar set-up to that shown in Figure 2 except that a 15 mm air gap is incorporated between the explosive under test and the cover. This arrangement was designed to remove the effect of those precursor waves [5] resulting from the jet impacting and penetrating the cover from affecting the explosive.

The cover and steel witness plate represent the confinement of the near and far side respectively of the munition case. The height of the explosive test samples are 50 mm or 100 mm depending on the type of test and hence are similar to the dimensions of the diameters of some in-service shells. The diameters of the test samples are 38 mm which is about 20 times greater than the diameter of the shaped charge jet. Thus the configuration of the explosive is a reasonable approximation to a filled munition from the point of view of jet attack.

In Figure 2 the shaped charge is held in the standoff tube at 2 charge diameters standoff (76 mm) from the top surface of the cover. This distance was selected to allow the development of the jet and is similar to that used in service warheads.

The test design is based on determining the critical "go-no go" detonation behaviour of the receptor explosive and the pattern of results is analysed statistically.

The sensitivity of the explosive is expressed as the thickness of the cover or barrier material which produces a 50% probability of detonation. Variation of the cover thickness alters the characteristics of the jet and shock entering the explosive. This arises since a shaped charge jet has a pronounced velocity gradient with the tip travelling considerably faster than the tail. For the jet from the MRL 38 mm diameter charge the tip velocity of 7.4 mm/ μ s decreases to about 2 mm/ μ s at the tail. Thus increasing the cover thickness decreases the jet and precursor wave velocities and vice versa. This statistical method of varying the stimulus on the explosive was developed by Dixon and Mood [10] and is similar to that used in many tests for assessing the sensitivity of explosives. The physical layout of the components resembles that in the Gap Test used for assessing the sensitivity of explosive to the shock from a standard detonating donor [11-15].

The standard form of the test uses a cover material of mild steel and a 38 mm diameter shaped charge containing a 42° apex angle, copper liner. Tests in which the characteristics of the components are altered are designated non-standard.

A compendium of jet sensitivity results is maintained for the explosives assessed on both the standard and non-standard forms of the test.

2.2 Description of Components

2.2.1 The Shaped Charge

The 38 mm diameter MRL shaped charge used as the standard donor in the test is illustrated in Figure 3. The liner is flow formed from oxygen free copper. The cast filling of Composition B (RDX/TNT/WAX, 55/45/1) has a density of $1.65 \pm 0.01 \text{ Mg/m}^3$ with 5% voidage and is checked for quality using static, orthogonal radiography. The fabrication technique has been described previously [16]. The charge is centrally initiated by an EBW detonator. At 2 charge diameters standoff the jet can penetrate about 180 mm of mild steel. The jet tip velocity has been measured with flash radiography as $7.4 \text{ mm}/\mu\text{s}$ [7] and the characteristics of the liner collapse process have been measured and modelled [17]. Jones [18] has developed a one dimensional model of the charge based on the analytical work of Pugh, Elchelberger and Rostoker [19] which shows good agreement with experiment. Recently the velocity gradient of the jet has been measured and the first 4 or 5 particles have been shown to have a similar velocity [21].

2.2.2 Standoff Tube

The nylon standoff tube is 2 shaped charge diameters long (76 mm), has an internal diameter of 38 mm and is fabricated by injection moulding. A recess in the top of the tube locates and coaxially aligns the shaped charge. Nylon was selected on the basis of its cost efficiency, low fragment damage and ease of penetration by X-rays for use in the instrumented firings using flash radiography.

2.2.3 The Cover

The covers for the standard test are machined from 75 mm diameter cold rolled mild steel. They are produced in a range of thicknesses from 5.0 mm up to 150.0 mm. Thickness tolerances are $\pm 0.05 \text{ mm}$ for the thinner covers and 0.1 mm for the thicker covers. End surfaces are ground flat and parallel in order to maintain intimate contact with the surface of the explosive test sample. All edges are made free from burrs. Steel was selected as the standard cover material on the basis of its widespread use as a munition casing, cost, availability and well defined properties.

In some non-standard tests, cover materials of aluminium, polymethylmethacrylate (plexiglas) and steel/plexiglas combinations are used. These materials were selected for their range of physical values (e.g. density) for use in investigative work and their use in ordnance engineering.

2.2.4 The Explosive Test Sample

Generally the explosive receptor is 38 mm diameter by 100 mm for the covered test and the same diameter but 50 mm long for the bare test. Tolerances for these dimensions are normally ± 0.05 mm. Experience has shown that for the shaped charge jet used in the test, these lengths of explosive are sufficient to allow discrimination between a building detonation and a fading reaction for the various jet initiation mechanisms occurring. Also, it is important that the geometry of the receptor is of sufficient size to avoid complications from explosive critical diameter effects and from shocks reflected off the explosive/witness block interface since the latter has been observed to cause backward moving detonations (termed a retonation) [9]. Thus the receptor charge diameter of 38 mm has been chosen to be orders of magnitude greater than the critical detonation diameter of most common explosives (a few millimetres [20]). Even the very large critical diameter of creamed TNT of about 15 mm is less than half the diameter of the standard test sample.

End faces of the charges are machined or pressed flat and parallel in order to maintain intimate contact with the cover and witness block. Receptor quality is checked with static, orthogonal radiography; cast charges with voids are rejected.

Some shorter charges are used when undertaking non-standard tests examining effects close to the cover/explosive interface.

2.2.5 The Witness Block

The 75 mm diameter witness blocks are machined from cold rolled mild steel to various lengths from 50 mm to 150 mm. Dimensional tolerances are ± 0.1 mm. The length used for a particular firing is selected to absorb the residual penetration of the jet. End faces are machined flat and parallel in order to make good contact with the explosive and firing stand. In some tests the witness blocks are sectioned to assess the jet's residual penetration.

2.3 Conduct of the Test

2.3.1 Procedure

The test is assembled as shown in Figure 2. In the majority of firings the required cover thickness is composed of more than one plate. When this occurs the number of plates is kept to the minimum and the thickest plate is placed in contact with the explosive. The latter helps maximise the recovery in one piece of that part of the cover in contact with the explosive in order to allow inspection of any retonation marks and other damage (see Figure 4a). The diameter of the retonation indentation is greatest at the critical cover thickness and hence can be a valuable aid in selecting the cover thickness for some of the ranging shots. The retonation dent diameter is dependent on the amount of the expansion of the explosive test sample between the time of the jet/shock penetration and the time to the distance where retonation commences.

During assembly care is taken to avoid any air gaps between the plates comprising the cover and at the cover/explosive interface. The final setup of the components is checked for coaxial alignment.

Following assembly and safety checks the round is fired and the steel witness block, cover and debris recovered and examined. Detonation produces a sharp dent in the steel witness block (see Figure 4b) whereas no dent is formed when the charge fails (see Figure 4c). However, in both cases the jet produces some penetration of the witness block. Jet alignment is assessed from the position of the penetration hole in the witness block with respect to the axis of the test arrangement. On the rare occasions that the full length of the explosive is not penetrated by the jet the round is repeated. As discussed above, damage to the underside of the cover plate can indicate whether a detonation occurred which guides the assessment of the result. Examination of any recovered explosive helps in the diagnosis of the type of failure. Thus the event can range from all the explosive being consumed close to the critical condition through the recovery of fine powder on the firing cell walls to the collection of large lumps of explosive showing some signs of surface melting.

The following procedure is used to vary the cover thickness and applies to tests on both covered and bare explosives. It is similar to the method for varying the barrier in the gap test [15]. A suitable cover thickness is chosen for the test explosive based on the results for similar compositions and its shock sensitivity as measured in the gap test relative to other explosives. If the round detonates then the cover thickness is increased by a substantial amount. Conversely if the round fails then the thickness is substantially decreased. The change in thickness of the cover in these ranging shots is based on previous results and examination of the recovered debris. The process is continued until a contradiction is produced and the detonation and failure results bracket the region of the critical thickness. Then the thickness of the cover is varied by the Bruceton 'up-down' method [10] using an interval of 5 mm for covers up to 75 mm thick, 10 mm for covers from 75 to 150 mm thick and 20 mm for thicker covers. The 'up-down' procedure is continued until a regular pattern of detonation and failures is obtained, usually this is between 10 and 20 shots. The cover thickness interval used throughout any test must, however, remain constant. Up until recently cover thicknesses were fabricated in imperial dimensions and thus the intervals ranged from 6.4 mm (0.25 in) up to 25.4 mm (1.0 in).

An example of a completed firing record is shown in Figure 5 for the test on covered Composition B and graphical representation of the 'go-no go' firing sequences for the tests on covered and bare Composition B are illustrated in Figures 6 and 7 respectively.

2.3.2 Method of Calculating Test Results

The test results are analysed statistically by the method of Dixon and Mood [10] to give the mean cover thickness, its standard deviation and 95% confidence limits. This critical cover thickness represents the detonation/failure threshold for the receptor explosive. Selection of the limits of the critical value is related to the statistical confidence required to obtain either a detonation or failure.

The critical cover is given by

$$m_{50\%} = c + d \left[\frac{\sum i n_i}{\sum n_i} \pm \frac{1}{2} \right] \quad (1)$$

- where c = smallest cover thickness at which detonation is recorded in the 'up-down' procedure.
- d = cover thickness interval between shots (i.e. 5, 10 or 20 mm).
- i = a number given to each cover thickness starting with c as zero.
- n_i = number of detonations/non-detonations (failures); use whichever has the smaller total number. Use a +ve sign in the equation when using detonations or a -ve sign when using non-detonations.

A completed proforma of the Dixon and Mood (10) statistical calculation for the covered Composition B test result is given in Figure 8 and the associated table and graphs are reproduced in the Appendix where $\sigma m_{50\%}$ is one standard deviation of the mean value ($m_{50\%}$), $L_{95\%}$ is the confidence limits and M, s and G are the parameters described in reference 10.

2.4 Important Test Parameters and Non-Standard Tests

As discussed in Section 2.1 sensitivity values are expressed in terms of the critical steel cover thickness and related to the velocity of the jet. However, there are other parameters of the jet and cover as well as the geometry of the explosive receptor which unless taken into account can affect the value of the measurements and complicate their interpretation. These factors have been controlled by selection of appropriate standard components and the test design.

Apart from velocity, jet diameter and density have been shown to play a role in explosive initiation (2-9). Jet velocity and diameter determine shock pressure and shape respectively while jet density is important in the energy transfer at the jet/explosive boundary and in determining the penetration of the cover. In the test both the diameter and density of the jet are fixed by the use of the standard shaped charge shown in Figure 3. However, non-standard tests have been carried out using shaped charges with different liner materials and diameters in order to determine parametric constants for the development of predictive equations for the detonation/failure threshold (9).

The important property of the cover is its density since this controls the jet penetration characteristics. Apart from the advantages listed in Section 2.2.3 steel has a relatively high density which has produced convenient critical thicknesses for the explosives in the covered configuration. Thus tests using Composition B receptors and the lower

density cover materials, aluminium and plexiglas, produced critical cover thicknesses of 127 and 201 mm respectively. The disadvantages of these greater cover thicknesses is that they increase the component handling and jet alignment requirements. (It should be noted, however, that the Composition B critical jet velocities for all three covers fell between 5.0 and 5.2 mm/ μ s [7]). Another advantage of a higher density cover is that the jet remains continuous for a greater range of jet sensitivity values (critical cover thicknesses) and hence avoids complications that may arise from the multiple impacts of a particulated jet.

3. TEST CALIBRATION

The test has been calibrated so that the measured critical thickness can be expressed as the critical jet velocity in air for the detonation/failure threshold of the explosive [21]. The calibration was undertaken by firing the jet from 2 charge diameters standoff (76 mm) through a range of steel cover thicknesses and using multiple flash radiography to measure the jet velocity and diameter about 15 to 30 mm from the exit surface of the cover. The curve constructed from these measurements is given in Figure 9 and allows the critical jet velocity to be read for a critical thickness determination. The jet penetration velocity at the exit surface of the cover can be determined from [22]:

$$U_p = \frac{V_j}{1+Y} \quad (2)$$

where U_p the jet penetration velocity in steel

V_j the measured jet velocity

Y the square root of the ratio of the steel cover and copper jet densities

Likewise the initial jet penetration velocity in an explosive test sample can be obtained from equation (2) but using the density of the explosive in the Y term.

Flash radiography showed that the jet remained continuous while penetrating steel covers up to about 125 mm thick; at greater thicknesses the jet emerged from the steel in particulated form with the distance between the particles increasing with steel thickness (i.e. time of flight).

The measured jet velocities for cover thicknesses less than about 20 mm were not consistent with the curve. This observation may be linked to the discovery in the measurements of the velocity gradient of the particulated jet that the first 3 to 5 particles have a constant velocity [9,21] and indicates that an instability exists in the jet that has not worked itself out at 76 mm standoff; this corresponds to about 18 μ s from the detonation wave hitting the apex of the copper liner. Such an instability has been reported

by Coughlin [23] in a numerical modelling investigation of the jet characteristics of a point initiated shaped charge. The charge studied was a scaled up version of the 38 mm diameter shaped charge except that the explosive head height was about the same.

The equation developed by DiPersio and Simon [24] for calculating the velocity of a stretching jet at a given depth of penetration in an incompressible target can be used as the basis for calculating a calibration curve of jet velocity versus cover thickness. However, the equation requires modification to take account of the constant velocity section at the front of the jet from the 38 mm diameter shaped charge. The modified equation takes the form [21]:

$$v_j = v_{tip} \left[\frac{r + s}{s + p} \right]^{-Y} \quad (3)$$

where v_{tip} the initial jet tip velocity

- r the depth of penetration from the cover surface
- s the standoff from the virtual origin position of jet formation to the start of penetration in the cover, and
- p the penetration depth of the cover produced by the cumulative length of the particles, x , in the constant velocity section at the front of the jet. x is obtained from flash radiography measurement and is related to p by [22]:

$$p = \frac{x}{Y} \quad (4)$$

The calculated calibration curve is drawn in Figure 9 and compares favourably with the experimental determination.

4. INSTRUMENTATION OF THE TEST

An instrumented form of the test assembly has been developed for the study of the mechanism and controlling parameters in the jet initiation of explosives [5]. The instrumented system utilises a similar arrangement to that shown in Figure 2 with the addition of a 300 kV flash radiography to observe and measure the jet, shock, detonation, retonation and disruption in the cover/explosive. Flash X-ray synchronisation is achieved by a flat electric sensor placed between the cover and receptor charge. Two orthogonal radiographs are taken for each firing. Delayed timing for the X-ray flashes is based on the calculated positions of the jet, shock or phenomenon under study and is obtained using a digital delay pulse generator. Usually several firings are conducted for each cover/explosive combination and where appropriate space/time plots are constructed. The known dimensions of the

explosive and steel components are used to obtain scaled measurements from the radiographs. Times can be recorded to $\pm 0.1 \mu\text{s}$ and distances on the flash radiographs can be measured to $\pm 0.2 \text{ mm}$. The X-ray cassettes are protected from the blast and fragments by layers of aluminium sheet and Lexan.

For various cover/explosive combinations the instrumented system has clearly identified the jet and its associated bow wave, detonation, retonation and deflagration in the receptor. These results have been discussed elsewhere [5-9] and are summarised in Section 6.

5. RESULTS

Table 1 lists the jet sensitivity values for 6 common explosives in the covered configuration. Table 2 lists the jet sensitivity values for 3 bare explosives. Cast and pressed explosives are listed in both sets of results. Sensitivity values are expressed both as the critical thickness of the steel cover and the critical jet velocity. The shock sensitivity as measured on the MRL small scale gap test [15] has been determined for each of the explosives and these values are included in Table 1 for comparison purposes.

TABLE 1

Jet Sensitivity Values for Steel Covered Explosives

Explosive		Jet Sensitivity		MRL Shock Sensitivity Test
Type	Density Mg/m^3	Critical Steel Cover Thickness $m_{50\%} (\sigma m_{50\%})$ mm	Critical Jet Velocity $m_{50\%}$ mm/ μs	
Creamed TNT	1.57	23.1 (2.7)	6.6	< 0
Composition B	1.65	59.8 (0.9)	5.2	0.40
H-6	1.74	69.7 (3.6)	4.9	0.42
Pressed TNT	1.52	105.4 (4.0)	4.1	1.22
Pressed Teteryl	1.48	135.8 (2.0)	3.5	2.84
Granular RDX	1.06	All Detonated		5.46

TABLE 2

Jet Sensitivity Values for Bare Explosives

Explosive		Jet Sensitivity	
Type	Density Mg/m ³	Critical Steel Cover Thickness m _{50%} (σm _{50%}) mm	Critical Jet Velocity m _{50%} mm/μs
Creamed TNT	1.57	19.8 (1.4)	6.8
Composition B	1.65	138.4 (2.6)	3.2
Pressed TNT	1.52	150.8 (2.0)	2.9

6. DISCUSSION6.1 Comments on Jet Sensitivity Results

The results listed in Tables 1 and 2 are for 3 cast, 2 pressed and 1 granular explosive. They include the aluminised composition H-6. The sensitivity values cover a wide range of both cover thicknesses and jet velocities. Further, the shock sensitivities of the same compositions as listed in Table 1 cover a wide range of values on the gap test scale. These observations suggest that the Jet Sensitivity Test operates over a wide scale and clearly differentiates between various compositions. The low standard deviation of the mean jet sensitivity values listed in the tables and illustrated by the "go-no go" firing frequencies in Figures 6 and 7 indicates that there is a sharp threshold between detonation and failure. This supports the validity of the test concept and together with the preceding observations leads to the conclusion that the test is an effective method of assessing the relative sensitivities of explosive fillings to shaped charge jets. However, note that the granular RDX detonated for all firings when the jet penetrated the cover and entered the explosive but always failed when the jet did not perforate the cover. Hence the uninstrumented form of the test may be limited in the study of explosives in the loose granular form.

Flash X-ray studies [5-9] have shown that the initiation of covered explosives generally arises from the bow wave shock in the explosive ahead of the jet. This type of shock initiation mechanism is supported by the comparison of the jet sensitivity and gap test values in Table 1 which can be seen to be in the same relative order. Further, note that in Table 1 pressed TNT is significantly more sensitive than creamed TNT although both have a similar density. Behaviour of this type is typical of shock sensitivity measurements on the two types of TNT and is attributed to the different physical state of the charges. Therefore it is concluded that properties

related to the physical state of the explosive are important in jet sensitivity, for example density, particle size and surface area, porosity, method of fabrication etc.

Comparison of the jet sensitivity values for Composition B and pressed TNT in Tables 1 and 2 shows they are considerably more sensitive bare than covered. The difference is attributed to the desensitisation of the explosive by the precursor wave that enters the explosive from the cover ahead of the jet. The precursor wave may be either the decaying shock from the jet impact on the cover or the bow wave from the jet penetrating the cover. However, comparison of the jet sensitivities for bare and covered creamed TNT shows they are similar. This behaviour is attributed to the large critical detonation diameter of creamed TNT (about 15 mm) compared to the jet (about 1.5 mm). Thus impact initiation is quenched by cooling reactions and subsequently the diameter of the bow wave from the jet penetrating the explosive builds up and expands to be greater than the critical size and detonation results.

6.2 Summary of Jet Initiation Mechanisms

The mechanisms of the jet initiation of covered explosives has been investigated by studies carried out at MRL and the Ballistic Research Laboratory, Maryland, USA. The results have been reported in several publications (5-9) and are summarised as follows.

When the jet hits the surface of the cover a large impact shock is produced. The impact shock propagates through the cover ahead of the jet but decays very rapidly. The penetrating jet sets up a bow wave that overtakes the impact shock within a few jet diameters of the cover surface. The characteristics of the bow wave are dependent on the properties of the jet and the host material. The jet and its bow wave continue steady penetration towards the cover/explosive interface. After passing through the interface either the decaying impact shock or the bow wave can alter the state of the explosive so that it is desensitized to the following jet. The stagnation pressure at the jet tip in the explosive is several times the magnitude of the bow wave pressure. It can also be several times the magnitude of the critical initiation pressure without detonation occurring. Thus bow wave desensitization is a major effect. When the jet penetrates the explosive a new bow wave is set up. Reaction occurs within the thickness of the bow wave and in sufficiently strong bow waves builds up to detonation.

Depending on the velocity of the jet and the cover thickness several types of event are possible.

- (a) For very thin covers and high jet velocities the impact shock can cause detonation. This occurs within a few millimetres of the explosive surface and before the arrival of the jet.
- (b) If the cover is more than a few jet diameters thick then the impact shock is attenuated before it reaches the explosive and the bow wave from the jet penetrating the explosive becomes the dominating mechanism for initiation. Strong bow waves will cause detonation within a few millimetres of the explosive surface.

- (c) As the jet velocity decreases with increasing cover thickness, the strength of the bow wave in the explosive decreases and the run distance and time to detonation increases. Thus near the critical condition, detonation in Composition B can take 11 μ s and 40 mm for initiation by the 38 mm diameter shaped charge jet.
- (d) For bow waves below the critical condition the explosive fails; the jet penetrates through the explosive with the bow wave causing disruption and/or reaction.
- (e) Jet bow waves reflected back into the explosive from a steel surface at the far end of short test samples can cause detonation. This has been observed near the critical jet initiation condition with explosive samples of up to 50 mm long for jets from the 38 mm charge and with samples up to 100 mm long for jets from an 81 mm shaped charge. This must be considered as a potential mechanism for initiation in munition systems, at least in smaller geometries with heavy confinement near the jet initiation threshold.

For covered explosives the studies have never observed initiation occurring directly at the jet tip; it has always occurred in the shock ahead of the jet or not at all. All of these mechanisms are a mode of shock initiation.

In the Jet Sensitivity Test on covered explosives events (b), (c) and (d) predominate for either side of the detonation/failure threshold. Mechanism (a) is unlikely since most cover thicknesses are considerably greater than a few jet diameters (the jet diameters of the 38 mm charge is about 1.5 mm at 2 to 4 charge diameter standoff) and mechanism (e) is discouraged by the use of long test samples.

Generally for bare explosives jet impact either causes detonation at (or very near) the surface of the explosive or the explosive fails. This mechanism appears to be replaced by that described in (c) above for explosives with large critical diameters for steady detonation with respect to the jet diameter. Flash radiography has shown that in the Jet Sensitivity Test bare Composition B and pressed TNT are initiated by the jet impact mechanism whereas creamed TNT is initiated by the bow wave in the explosive (mechanism (c) above) as discussed in Section 6.1. Bare explosive jet initiation has also been extensively studied by Mader and Pimbley [3] using a numerical modelling technique.

7. CONCLUSIONS

A calibrated test has been developed for the assessment of the sensitivity of covered and bare explosives to a shaped charge jet. Explosive sensitivity is expressed both in terms of the critical thickness of steel in front of the explosive and the critical velocity of the jet that allows detonations in 50% of a series of firings. Important test parameters have been identified.

Sensitivity values have been measured for explosives in both the covered and bare configurations. Generally bare explosives were found to be significantly more sensitive than covered explosives.

An instrumented form of the test arrangement has been developed to study the mechanisms of jet initiation of explosives.

8. ACKNOWLEDGEMENTS

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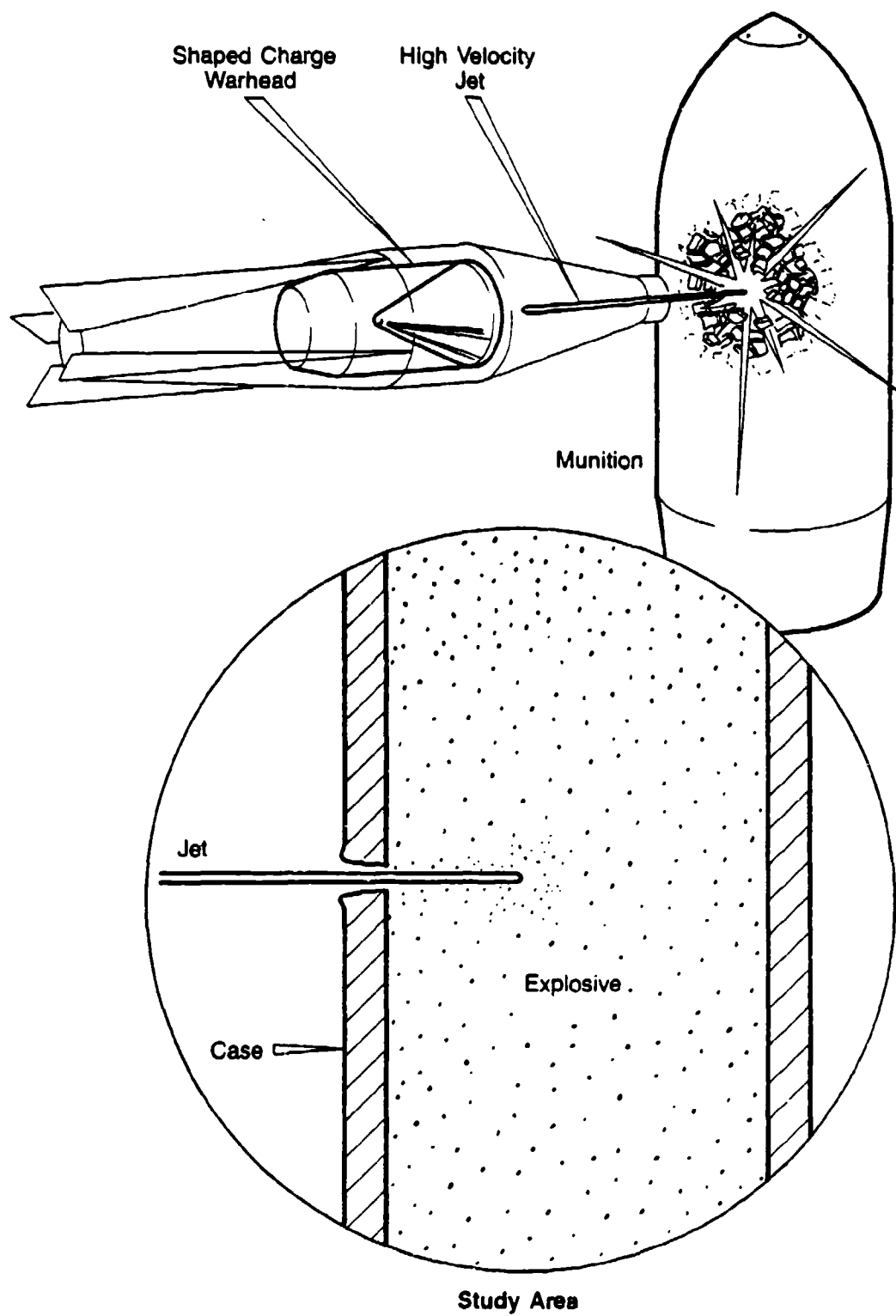


FIGURE 1 Basis for the Design of the MRL Jet Sensitivity Test

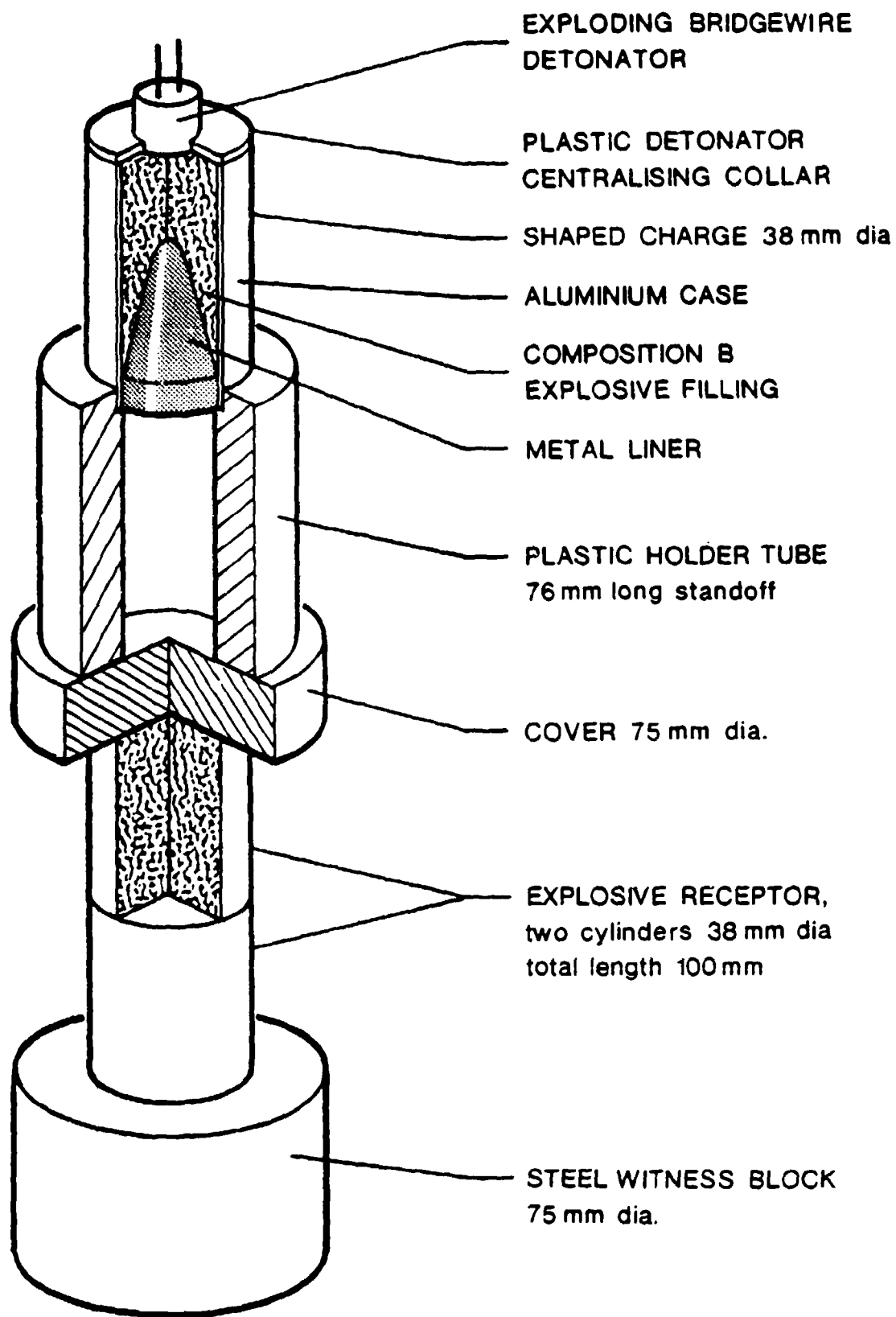


FIGURE 2 Assembly for the MRL Jet Sensitivity Test on Covered Explosives

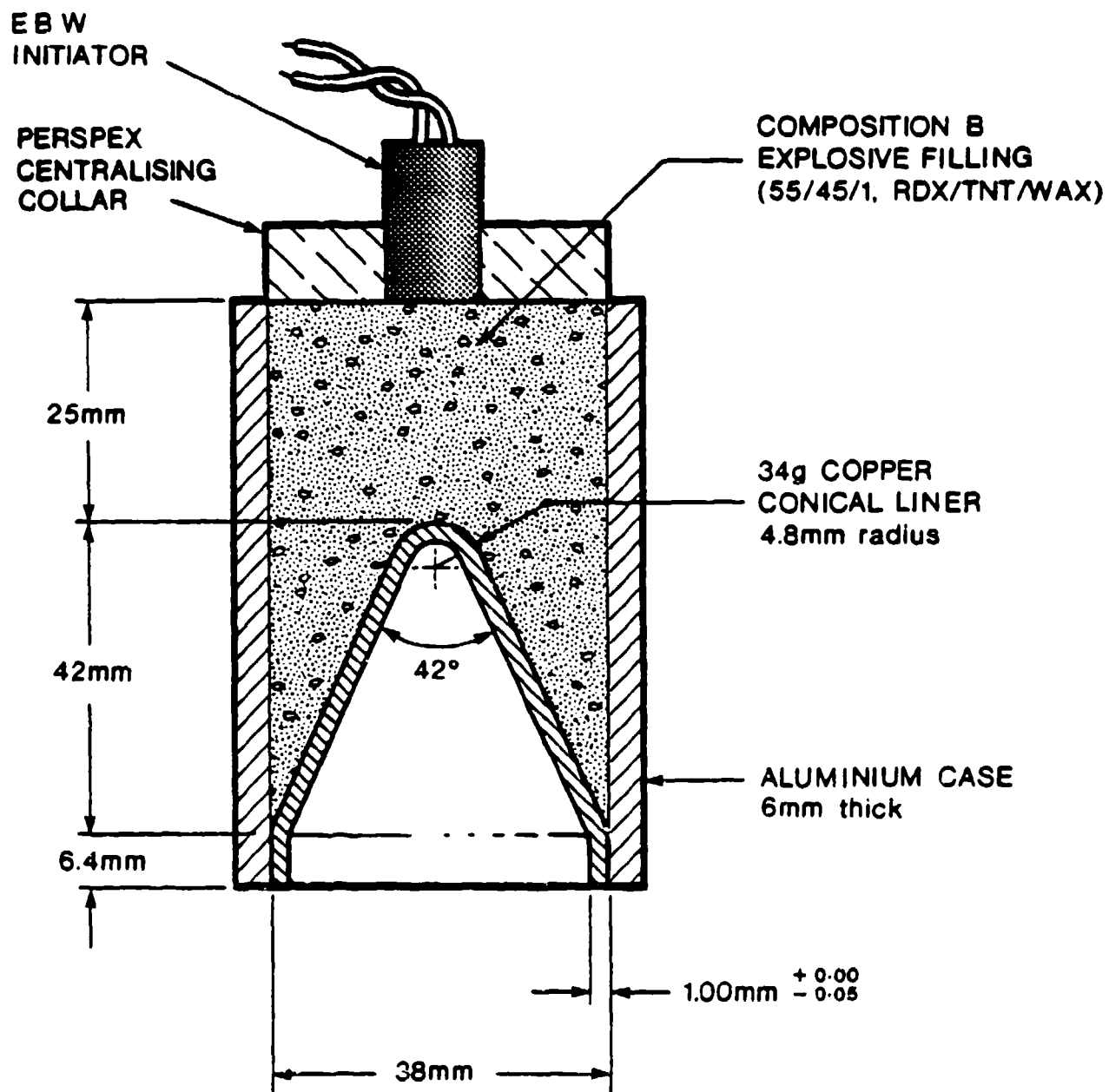


FIGURE 3 The MRL 38 mm diameter shaped charge



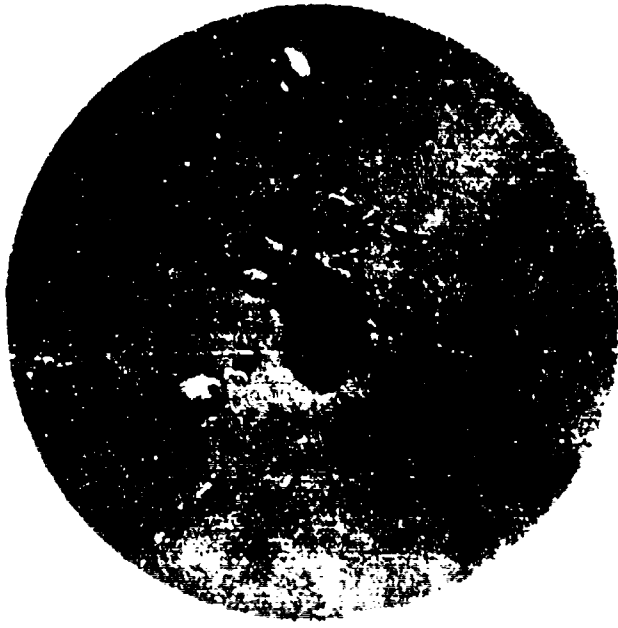
a

Underside of cover showing double circular indentation typical of a detonation. Note the slug protruding from the hole made by the jet.



b

Top of witness block showing indentation from a detonation and residual jet penetration.



c

Top of witness block for a failure showing only residual jet penetration.

FIGURE 4 Examples of the damage to the mild steel covers and witness blocks recovered from the test on covered Composition B. Many of the other explosives tested show similar behaviour. The components are 75 mm diameter.

FIGURE 5

**Completed Firing Record for the Measurement of the Jet
Sensitivity of Covered Composition B**

JET SENSITIVITY TEST: COVERED COMPOSITION B STANDARD TEST

Date of Test	OCT 1973	OIC	L. LEARMONTH/R. RIX
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A. DESCRIPTION OF EXPLOSIVE MATERIAL TESTED

Type	COMPOSITION B	Composition	RDX/TNT/WAX, 55/45/1
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Details of Fabrication	Cast into 50 mm dia by 300 mm cylinders. Header removed. Machined into 38 mm dia by 50 mm cylinders
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Density	1.65 Mg/m ³	Additional Data	Test charge length 100 mm (2 cylinders)
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B. TEST CONDITIONS

Type of Shaped Charge	MRL STANDARD 38 mm DIA	Set-up	Standard
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Cover Material	MILD STEEL	Additional Data	STANDARD TEST
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C. TEST RESULTS

CODE: D = Detonation, ND = Non-Detonation

No	Charge No	Cover (mm)	Res	No	Charge No	Cover (mm)	Res	No	Charge No	Cover (mm)	Res
1	521	63.6	ND	9	527	63.6	ND	17	585	63.6	ND
2	567	57.2	D	10	576	57.2	D	18	580	57.2	D
3	523	63.6	ND	11	528	63.6	ND	19	586	63.6	ND
4	568	57.2	D	12	577	57.2	ND	20	584	57.2	D
5	524	63.6	ND	13	522	50.8	D	21	593	63.6	ND
6	569	57.2	D	14	578	57.2	D	22			
7	526	63.6	ND	15	529	63.6	ND	23			
8	570	57.2	D	16	579	57.2	D	24			

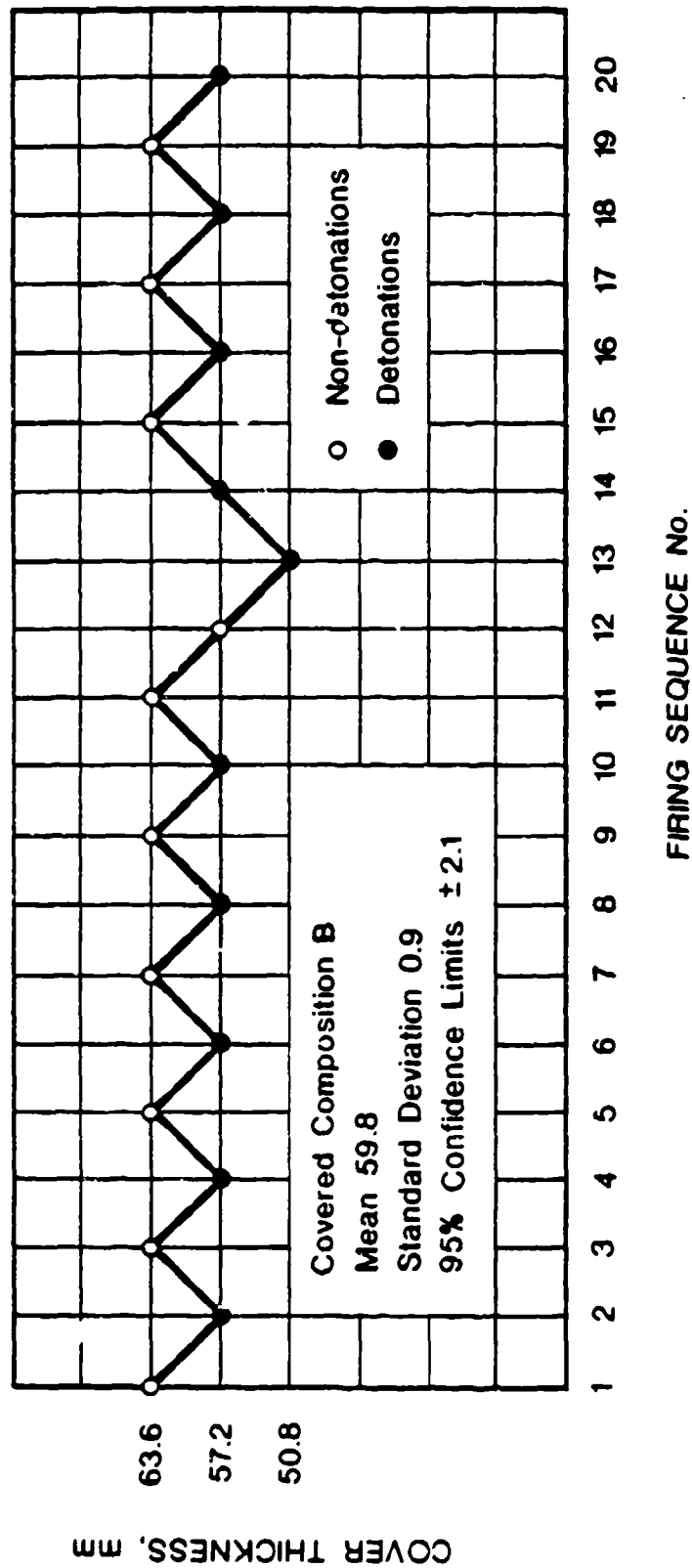


FIGURE 6 "Go-no go" Firing Sequence and Results for the Measurement of the Jet Sensitivity of Covered Composition B

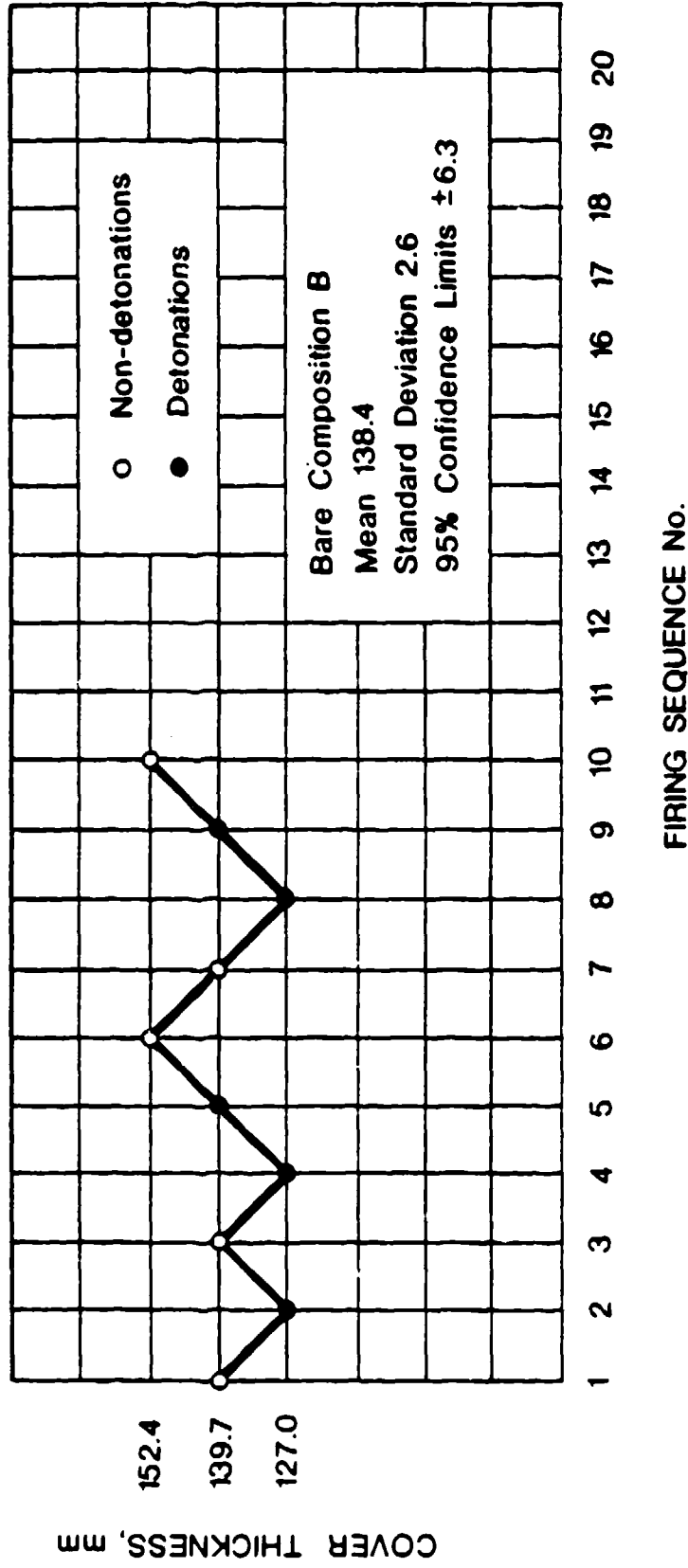


FIGURE 7 "Go-Nogo" Firing Sequence and Results for the Measurement of the Jet Sensitivity of Bare Composition B.

FIGURE 8

Completed Proforma for the Dixon and Mood Statistical
Calculation for the Critical Thickness of Covered Composition B

JET SENSITIVITY TEST : COVERED COMPOSITION B STANDARD TEST
CALCULATION SHEET FOR DIXON AND MOOD STATISTICAL ASSESSMENT

Date	FEBRUARY 1974	Assessor	M. CHICK			
Smallest Cover Thickness (c)		50.8 (mm)	Cover Thickness Interval (d)		6.4 (mm)	
Test Cover Thickness (mm)	No. of Detonations (use + in eqn 1)	No. of Non-Detonations (use - in eqn 1)	1	n ₁	1n ₁	1 ² n ₁
A (c) 50.8	1	0	0	1	0	0
S 57.2	9	1	1	9	9	9
C 63.6	0	9	2	0	0	0
E			3			
N			4			
D			5			
I			6			
N			7			
G			8			
			9			
TOTAL = 10		TOTAL = 10	Σ	10	9	9

NB c = smallest cover thickness used in calculations

n = number of detonations or non-detonations - if different use whichever has the smaller total number

$$(1) \quad m_{50\%} = c + d \left[\frac{\sum 1n_1}{\sum n_1} \right] \pm 1/2 = 50.8 + 8.96 = \underline{59.8}$$

$$(2) \quad M = \left[\frac{\sum 1^2 n_1}{\sum n_1} \right] - \left[\frac{\sum 1n_1}{\sum n_1} \right]^2 = 0.9 - 0.81 = \underline{0.09}$$

$$(3) \quad s = \underline{0.31} \quad (\text{From Dixon and Mood Table 1 and Graphs I \& II})$$

$$(4) \quad G = \underline{1.5} \quad (\text{From Graphs III \& IV})$$

$$(5) \quad \sigma = sd = \underline{1.98}$$

$$(6) \quad \sigma_{m_{50\%}} = \frac{\sigma G}{\sqrt{\sum n_1}} = \underline{0.94}$$

$$(7) \quad L_{95\%} (m_{50\%}) = m_{50\%} \pm 1.96 \left[\frac{\sum n_1 + 1.2}{\sum n_1} \right] \sigma_{m_{50\%}} = \underline{59.8 \pm 2.1}$$

$$= \underline{57.7 \& 61.9}$$

$m_{50\%} = 59.8$	$\sigma_{m_{50\%}} = 0.94$	$L_{95\%} (m_{50\%}) = 59.8 \pm 2.1$
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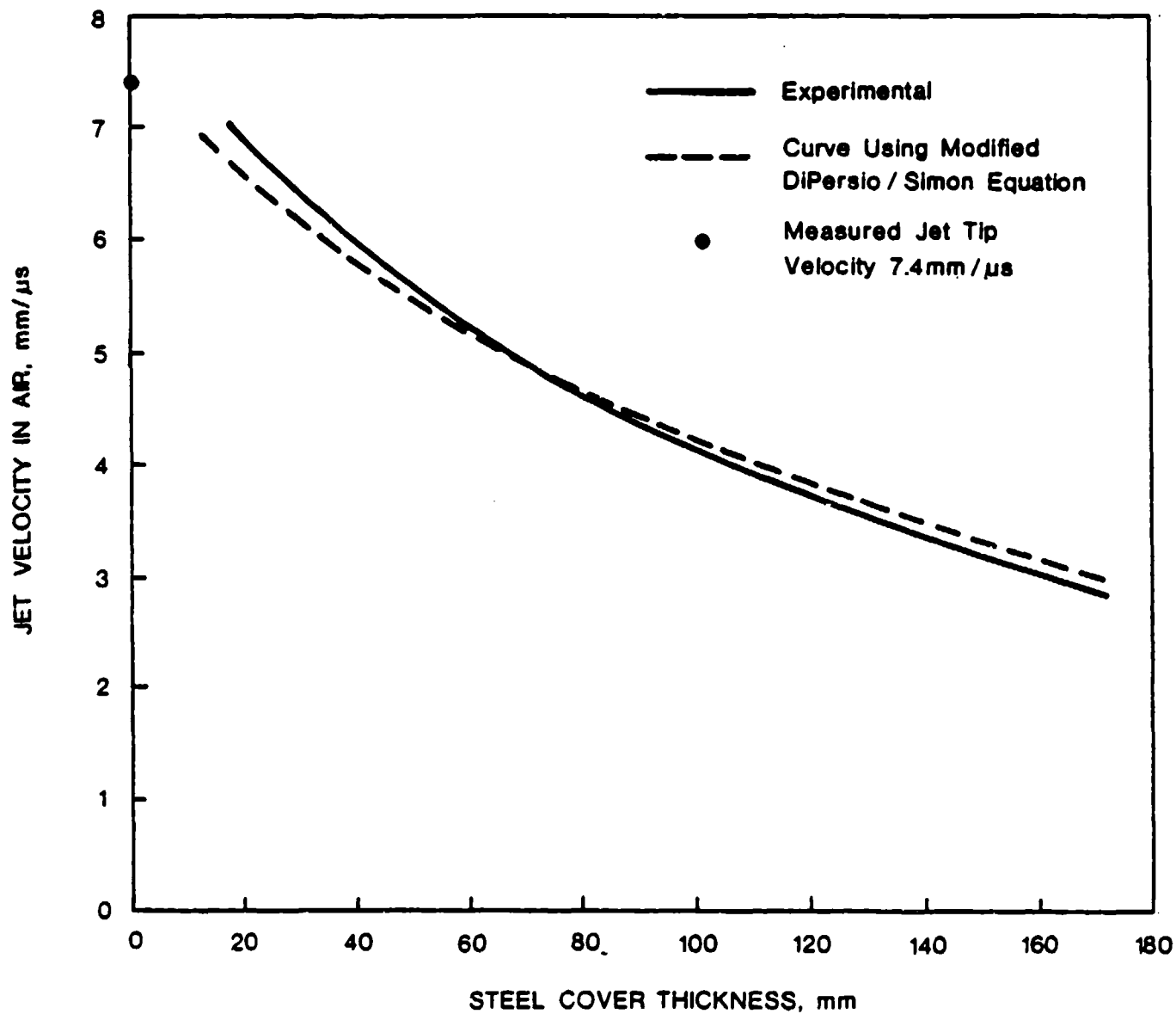


FIGURE 9 Jet Sensitivity Test Calibration Curve of Jet Velocity vs Steel Cover Thickness

APPENDIX

TABLE AND GRAPHS USED IN THE DIXON AND MOOD

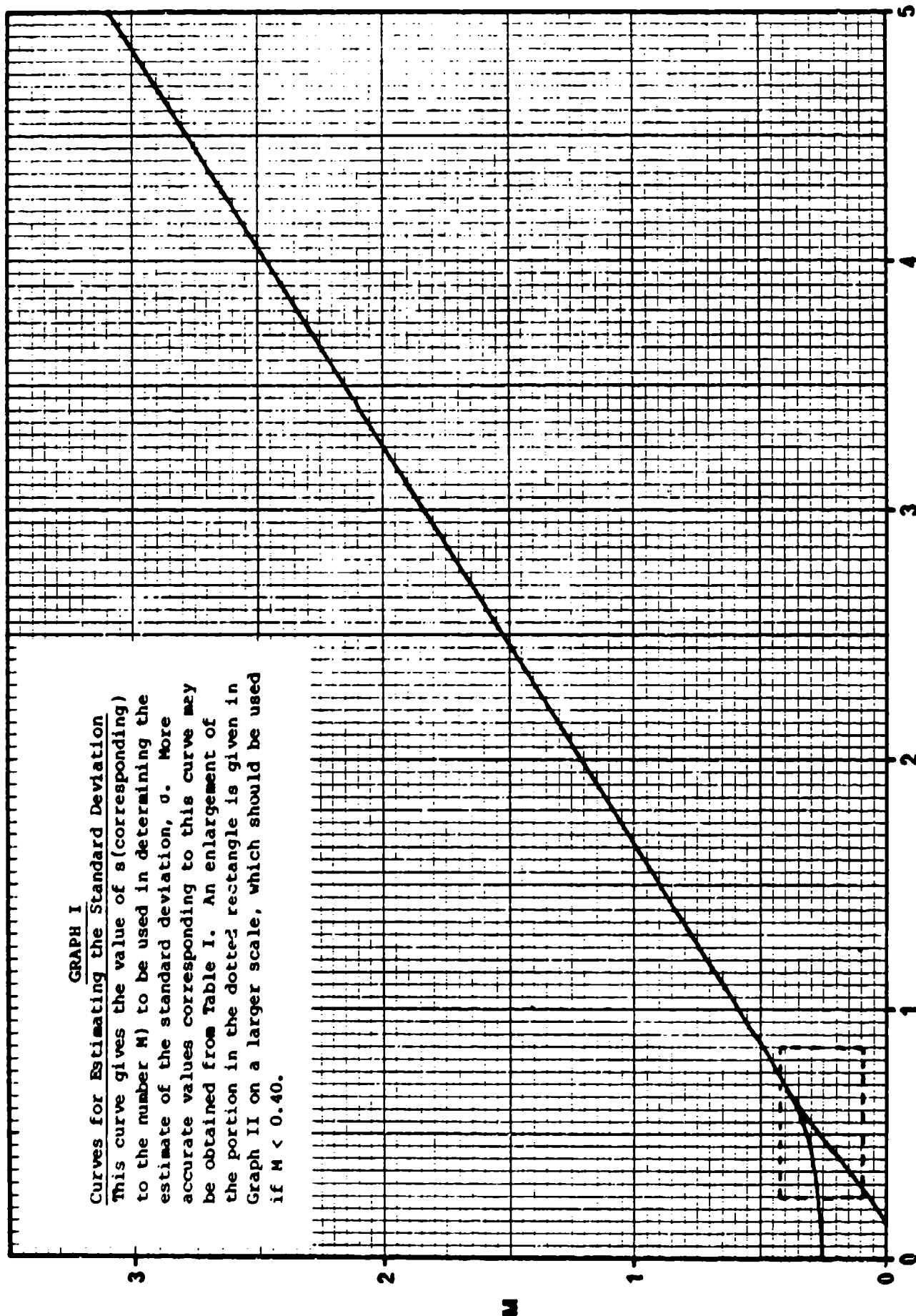
STATISTICAL ANALYSIS TO OBTAIN THE CRITICAL COVER THICKNESS

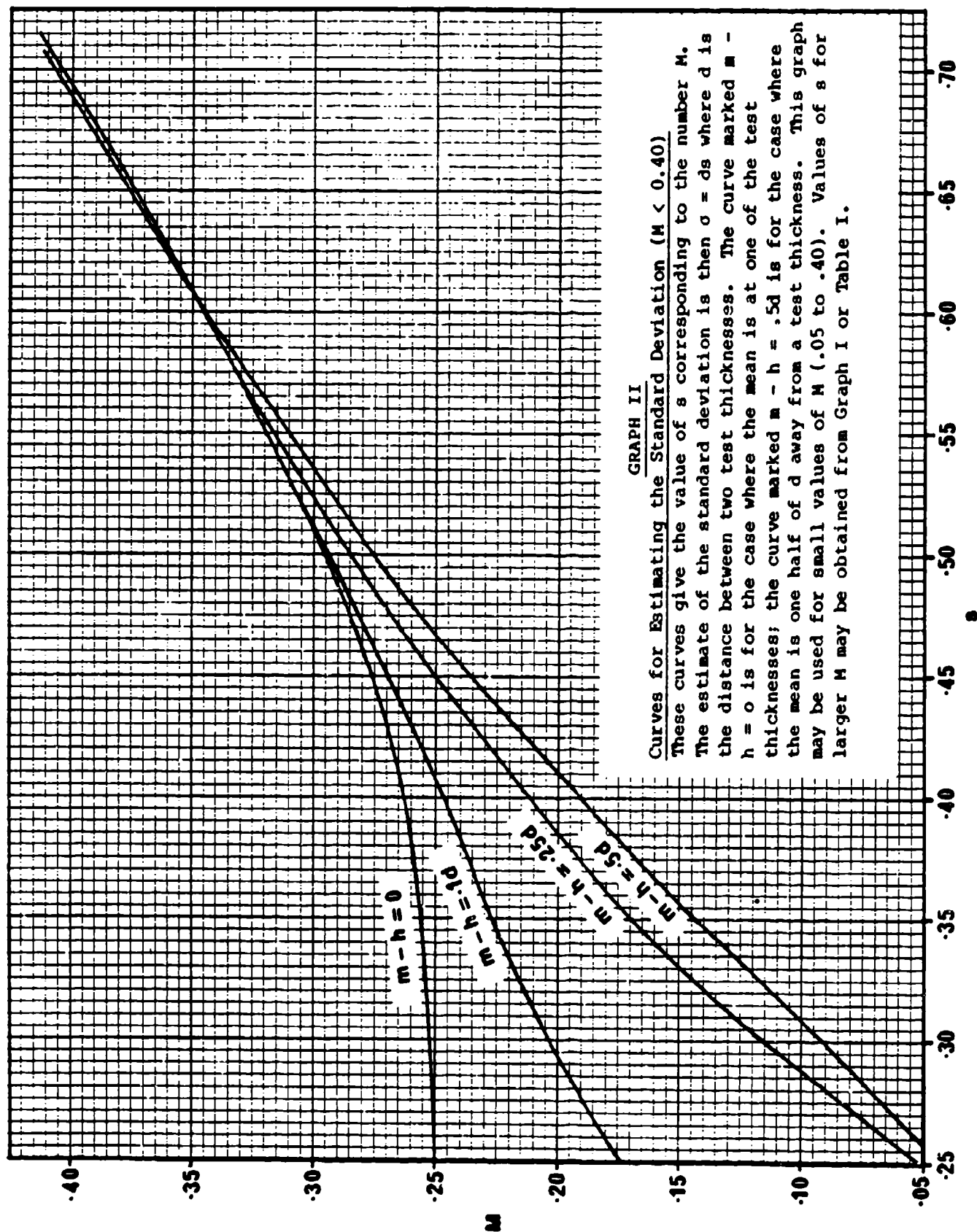
TABLE I Table of s for Obtaining the Sample Standard Deviation

[illegible]

GRAPH I

Curves for Estimating the Standard Deviation
 This curve gives the value of s (corresponding to the number M) to be used in determining the estimate of the standard deviation, σ . More accurate values corresponding to this curve may be obtained from Table I. An enlargement of the portion in the dotted rectangle is given in Graph II on a larger scale, which should be used if $M < 0.40$.





GRAPH II

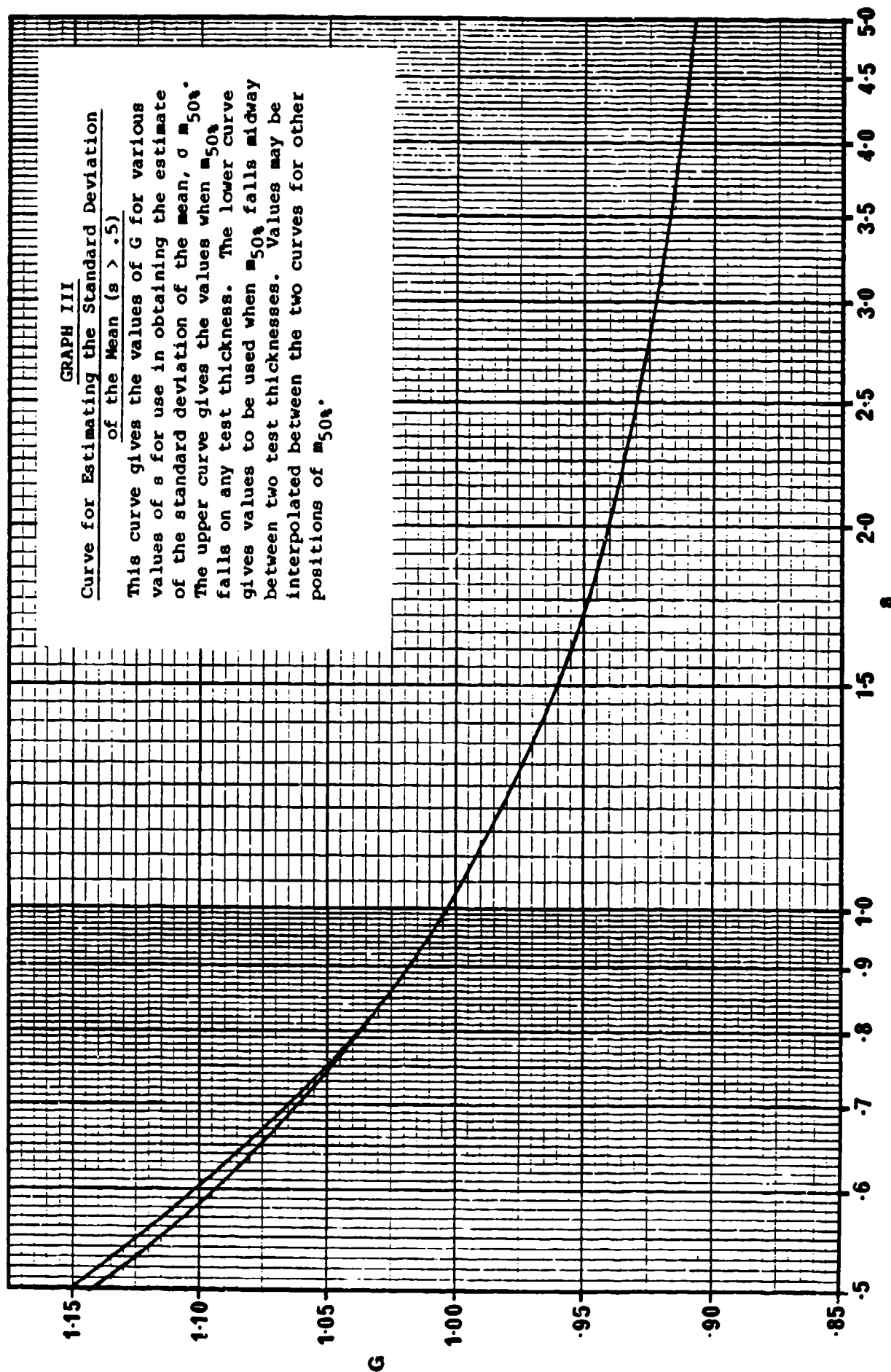
Curves for Estimating the Standard Deviation ($M < 0.40$)

These curves give the value of s corresponding to the number M . The estimate of the standard deviation is then $\sigma = ds$ where d is the distance between two test thicknesses. The curve marked $m-h = 0$ is for the case where the mean is at one of the test thicknesses; the curve marked $m-h = .5d$ is for the case where the mean is one half of d away from a test thickness. This graph may be used for small values of M (.05 to .40). Values of s for larger M may be obtained from Graph I or Table I.

GRAPH III

Curve for Estimating the Standard Deviation of the Mean ($s > .5$)

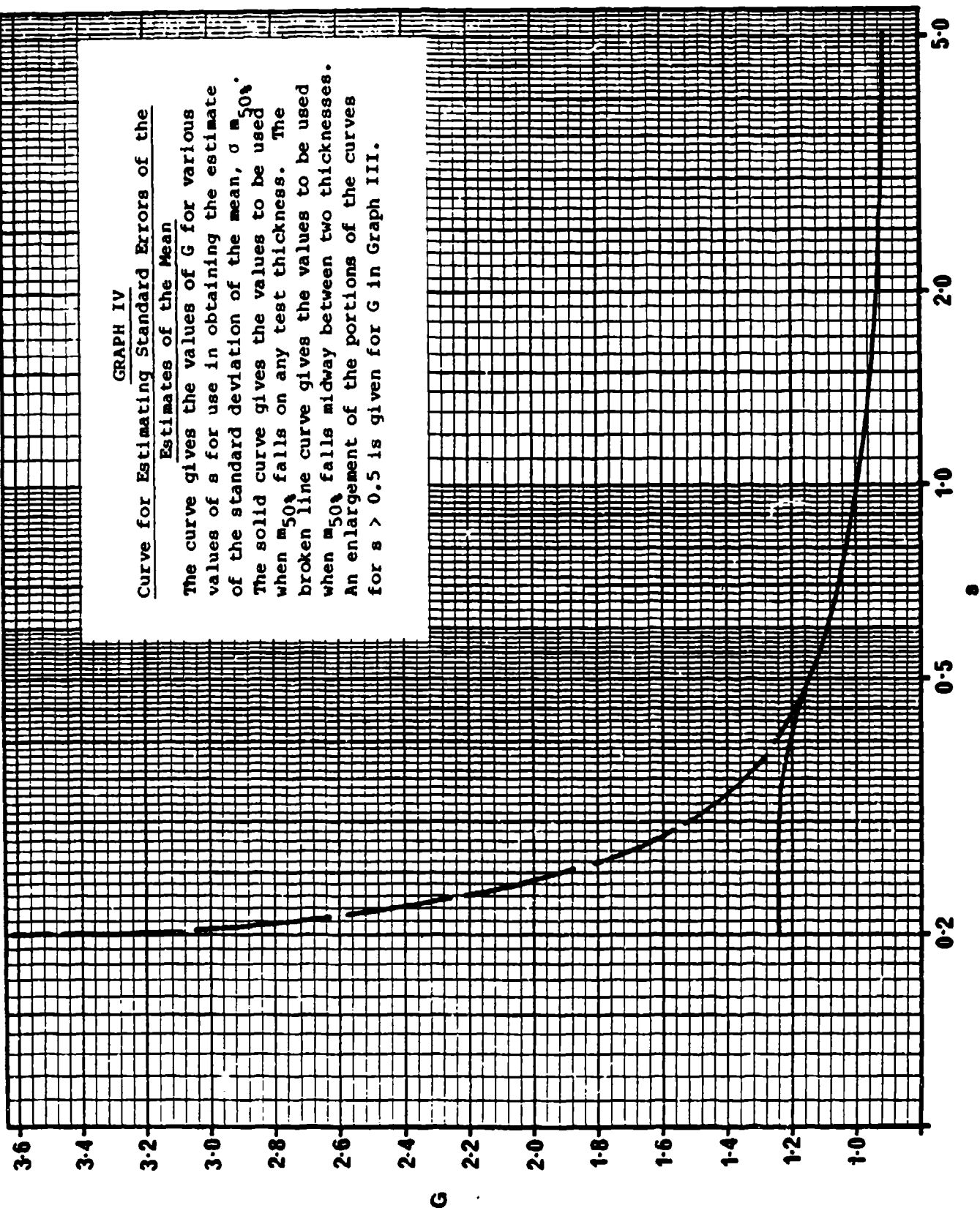
This curve gives the values of G for various values of s for use in obtaining the estimate of the standard deviation of the mean, $\sigma_{\bar{x}}$. The upper curve gives the values when $\bar{x}_{50\%}$ falls on any test thickness. The lower curve gives values to be used when $\bar{x}_{50\%}$ falls midway between two test thicknesses. Values may be interpolated between the two curves for other positions of $\bar{x}_{50\%}$.



GRAPH IV

Curve for Estimating Standard Errors of the
Estimates of the Mean

The curve gives the values of G for various values of s for use in obtaining the estimate of the standard deviation of the mean, $\sigma_{\bar{m}_{50\%}}$. The solid curve gives the values to be used when $m_{50\%}$ falls on any test thickness. The broken line curve gives the values to be used when $m_{50\%}$ falls midway between two thicknesses. An enlargement of the portions of the curves for $s > 0.5$ is given for G in Graph III.



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